Chapter 20

Auxiliary detectors

20.1 Fiber beam monitors

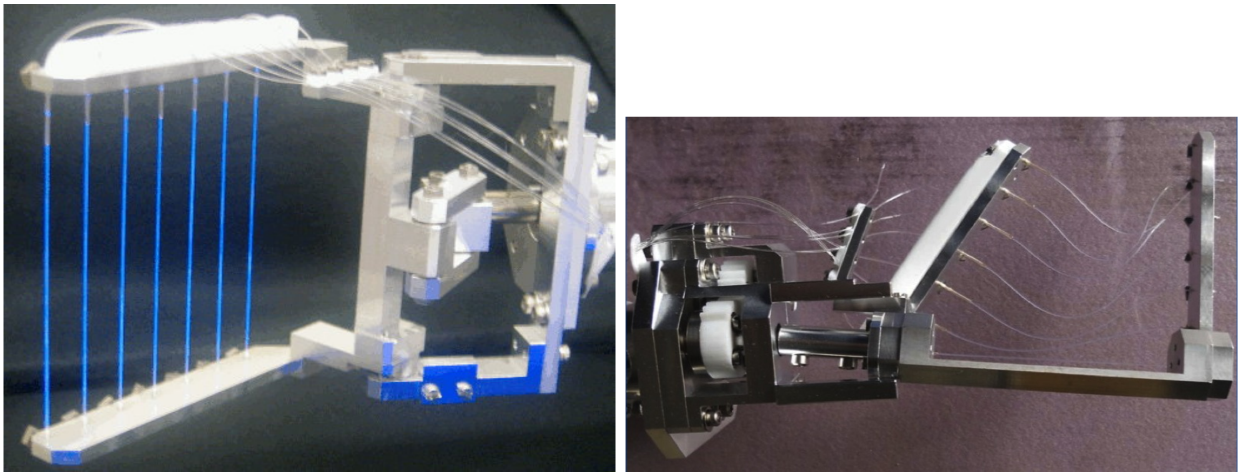
20.1.1 Requirements

The fiber beam monitor system is designed to serve three purposes:

- As a commissioning instrument, to determine the position (x, y) and angle (x', y') of the beam at injection. (These coordinates are defined in Section 8.3.2.)
- To monitor the evolution of these beam properties during the kick and scraping phases.
- To observe and directly characterize periodic beam motion, notably the modulation of beam centroid position and width by coherent betatron oscillations, as described in Chapter 4.

In order to serve these purposes, the fiber beam monitor system is subject to the following requirements:

- The pulse width and deadtime must be much less than one cyclotron period of 150 ns, by at least one order of magnitude.
- The system must be able to characterize a muon beam whose intensity ranges from 5% to 200% of the expected number of muons (1.8×10^4) that are captured in the storage ring.
- The spatial resolution of each detector must be sufficient to observe the transition from x' to x and from y' to y over a 90° phase advance. (The procedure for this analysis is described in Ref. [1].)
- The detector must be able to reside in a vacuum of 10^{-6} Torr, with a vacuum load of less than 5×10^{-5} Torr L/s.
- The detector must be able to function in a 1.5 T magnetic field.
- The detector must not perturb the local magnetic field by more than 10 ppm. There must be no transient field perturbations of less than 1 ms duration except during special runs when the detector is activated and inserted.



(a) (b)

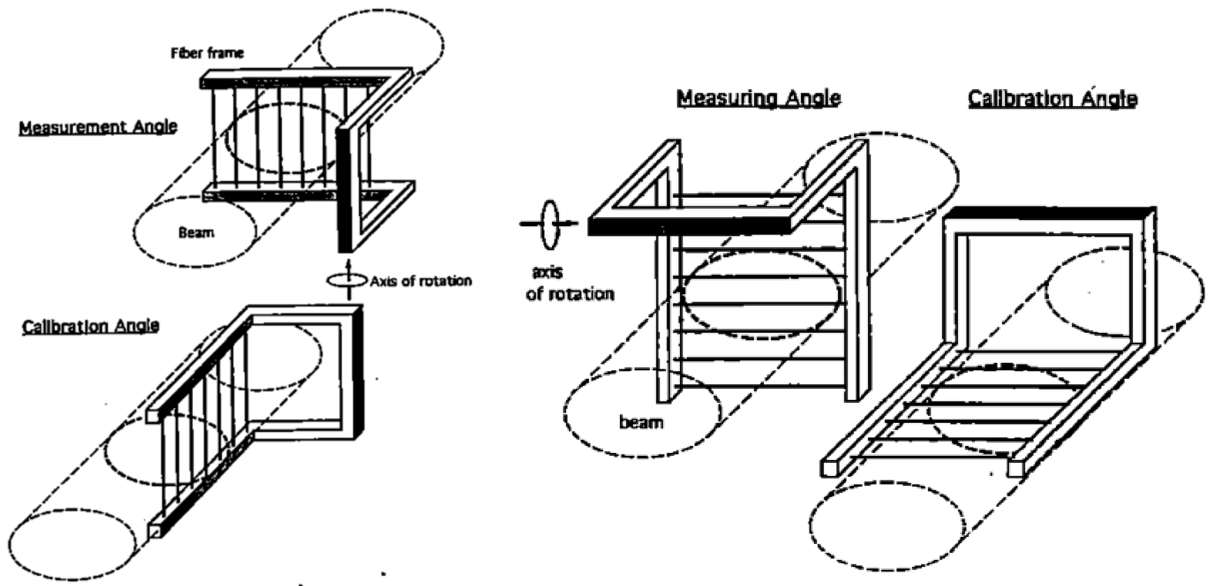
Figure 20.1: (a) The 180° x-profile monitor, glowing under ultraviolet illumination in the laboratory. (b) The 270° y-profile monitor, which was found to be damaged when it was removed from the Brookhaven E821 storage ring.

20.1.2 Recommended Design

The fiber beam monitors were originally built for E821 by a group at KEK that is not part of the Fermilab collaboration [2, 3]. We intend to refurbish and reuse all components from the existing system that remain suitable.

Each fiber beam monitor holds a "harp" of seven scintillating fibers of 0.5 mm diameter, each 90 mm long and separated from its neighbors by 13 mm, as shown in Figure 20.1(a). Each scintillating fiber is bonded to a standard optical fiber that connects it to a vacuum feedthrough. There are a total of four devices, and they are deployed near the 180° and 270° positions in the ring. The two 180° fiber beam monitors should observe an image of the beam as it was injected at the inflector, while the two 270° fiber beam monitors should map x' and y' at the inflector into x and y at 270°. At each location, one fiber beam monitor suspends the fibers vertically to measure in x, and the other arranges them horizontally to measure in y. The fibers stay inside the vacuum, and they can be plunged into the beam path. As shown in Figure 20.2, they can be also rotated into a horizontal plane, where all fibers see the same beam, for calibration, or upright for measurement. Because ferromagnetic material cannot be placed this close to the precision magnetic field, aluminum motors and actuators driven by compressed air are used for this motion.

Three of the four fiber beam monitors recovered from E821 appear to be in mechanically good condition. One fiber beam monitor (the 270° y-profile monitor) was found to be significantly damaged, with a snapped fiber and bent frame components, as shown in Figure 20.1(b). This damage may have existed since early E821 runs; an unexpectedly high muon loss rate when the fiber harps were inserted suggests that there were unintended scattering sources in the beam. We have disassembled the affected part of the damaged harp and found that there is one aluminum part that will need to be replaced, along with a shaft that has already been straightened and a few bent screws. The work to fabricate the replacement



(a) (b)

Figure 20.2: Rotational motion corresponding to the calibration and measurement positions for (a) x and (b) y. This figure is reproduced from [3].

part has already begun.

In addition to the fiber that is completely broken on this harp, another shows visible indications of strain. There are also two broken and one strained fibers on the 180° x-profile monitor, and two fibers on the 180° y-profile monitor are broken at the tips so that they are not supported rigidly. As laboratory testing has proceeded, we found other broken and damaged fibers; they break accidentally with very little force. Also, as shown in Figure 20.3, we have measured the photoelectron yield of an existing fiber taken from a harp and compared it with that of two new fiber samples provided by Kuraray. We can expect a factor of 2.7 more light (4.2 versus 1.6 photoelectrons) from a new fiber. Consequently, we are developing a reliable, reproducible technique to replace all of the fibers.

We initially tested a technique that yields a mechanically stable connection with no visible gap between two polished fibers: holding one of the fibers from below with a clamp, placing a 1 cm length of 24-gauge light-wall PTFE tubing over it, dispensing a drop of optical cement into the tubing with a needle, and inserting the second fiber from above. When the fibers were cleaned and polished properly before being joined, we observed transmission of 71% with this method. This agrees with the result of Ref. [4], which reports on a similar method, and with the 69% transmission that we measured for an existing glue joint that broke from a harp.

We attribute the light loss primarily to stripped cladding at the ends of the fibers, so we are now refining a technique that relies less on mechanical polishing. The scintillating and clear fibers will be embedded in a hole drilled in a block of PTFE, cemented in place with a vacuum-compatible epoxy. The blocks as a whole will be flycut with a polycrystalline diamond cutter; only minimal fine polishing of the block with 1 micron and 0.3 micron

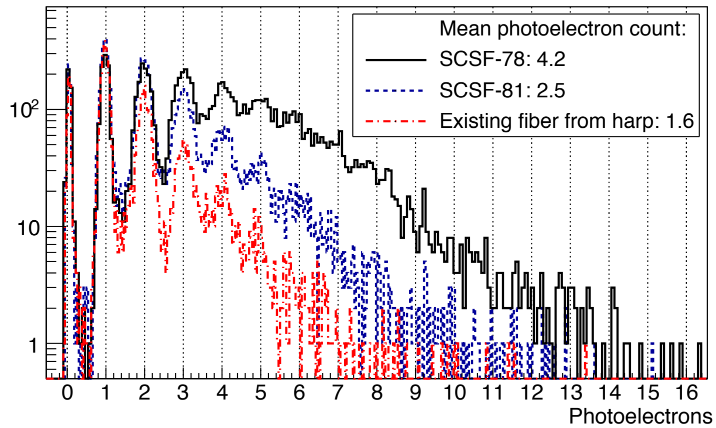


Figure 20.3: Number of photoelectrons per minimum ionizing event from a ^{90}Sr beta source for two new fiber samples provided by Kuraray, in comparison to an existing fiber that broke from one of the harps.

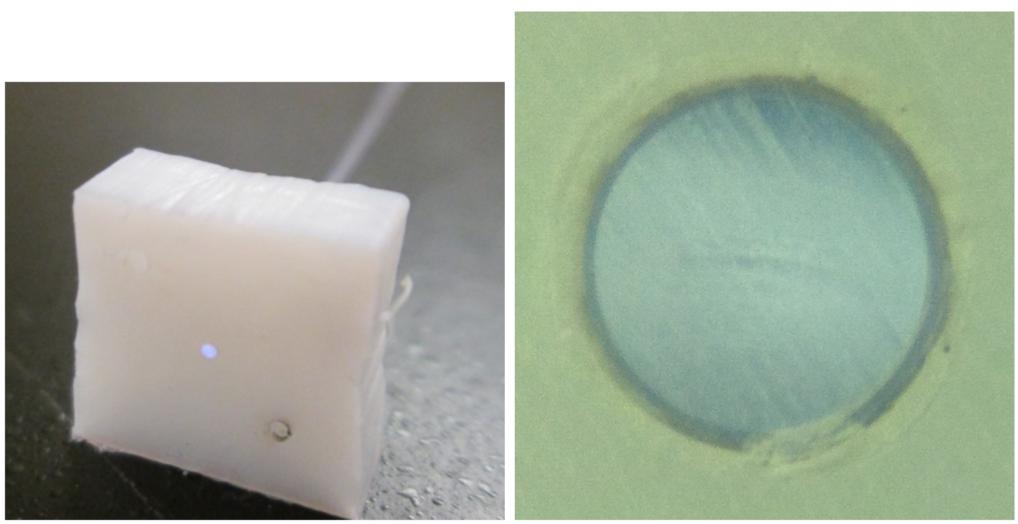


Figure 20.4: Two views (microscopic view on right) of a scintillating fiber that has been flycut inside a PTFE block. We are continuing to improve the procedure to minimize the remaining surface roughness and cladding separation.

lapping paper will be needed as a final step. Alignment holes are drilled in the blocks to allow the fibers to be held together temporarily with M1 screws while an optical adhesive between them cures. Figure 20.4 shows a block with a single scintillating fiber for testing; the eventual intent is to embed all 7 fibers from one harp in a single connector block. A first test with this fiber has shown transmission of 77% from a scintillating to a clear fiber, and we are continuing to improve the technique.

We have cleaned the exterior parts of all of the fiber harps, and three of them have been tested through their full range of motion using a prototype of a new motion control system. After repairs are completed to the damaged harp, we expect to be able to do the same for it. Similarly, we will test and assure the vacuum integrity of the system before returning the fiber harps to Fermilab. We have already successfully tested one harp by observing the rate of pressure rise with a computer-interfaced Pirani gauge after a turbomolecular pump is valved out. After about a day of pumping, the rate was 2×10^{-5} Torr L/s.

In E821, the fibers were read out with conventional photomultipliers in a remote location, at the end of a long fiber, where the magnetic field was reduced. Replacement by SiPMs mounted directly on the fiber harps will allow the long fiber to be eliminated. SiPMs also have higher photon detection efficiency than conventional photomultipliers. Initial SiPM tests have been conducted with the Hamamatsu S10362-11-050C, for which we have developed a readout board with a simple two-stage voltage preamplifier. It has a 1×1 mm^2 area that is suitable for fiber readout applications.

This SiPM is a reasonably appropriate match to the estimated number of photoelectrons, although a model with more pixels remains under consideration as an alternative. A GEANT4 simulation indicated that the most probable energy deposit is 0.06 MeV in each interaction, leading to approximately 6 photons at the SiPM. The proposed SiPM, with ∼65% quantum efficiency and 61.5% fill factor, would therefore yield 2.4 photoelectrons per interaction. This is less than the result shown in Figure 20.3 because it allows for some losses at the scintillating-to-clear fiber boundary and at the vacuum feedthrough. Approximately 1% of stored muons should interact with a central fiber in each turn. The rate calculation summarized in Table 5.1 shows that we can expect 1.8×10^4 on the initial turns around the ring. This would lead to 432 photoelectrons reaching the SiPM, which does have the potential to saturate the 400 available pixels; however, if too much light really becomes an issue, it would be straightforward to insert an attenuating filter. The maximum dark count rate of 800 kcps would give one photoelectron of noise every 8 cyclotron periods, which is very small compared to the expected amount of light. To fully cover the fibers on each of the four monitors, we need 28 SiPMs. We have acquired 30 Hamamatsu S10362-11-050C devices that were left unused by a project at Argonne National Laboratory.

The SiPM requires a preamplifier. For laboratory tests, we are currently using a design based on a circuit developed by the electronics group at the Paul Scherrer Institute and used in several experiments there [6, 7]. It uses two stages of Mini-Circuits MAR-series gain-block amplifiers separated by a pole-zero cancellation. A schematic of this circuit, appropriately adapted for the fiber harp application, appears in Figure 20.5. A prototype of this circuit has been constructed, and the full width of the pulse is ∼10 ns, which is more than sufficient for the required time resolution. Because the signal will be recorded by the new waveform digitizer modules that are being developed for the calorimeters, we plan to replace the second stage in this design with the same LMH6881 programmable-gain differential amplifier that is used on each crystal. Prior to installation, we will test the magnetic susceptibility of the new preamplifier, which is the only really new part of the system; the rest of the fiber harp was demonstrated in E821 to be compatible with the requirements of the precision field.

Waveforms from these SiPMs will be recorded by the same waveform digitizer that is being developed for the calorimeters; an additional MicroTCA crate will be located near the center of the storage ring for this purpose.

20.2 Entrance counters

20.2.1 Requirements

The time at which the muon bunch enters the ring must be subtracted from the time of each decay positron in order to align data from different fills properly. The relative intensity of each fill is also monitored. An entrance counter, positioned just outside the inflector, is needed to record the time and intensity of each fill. In E821, the cyclotron "fast rotation" structure, described in Section 4.3.1, was removed by adding a uniformly distributed pseudorandom number from zero up to the cyclotron period ($\sim$150 ns) to the entrance time of each bunch. This procedure, which will presumably be needed again in the new experiment, artificially degrades the time resolution of the entrance counter, setting the scale of the requirement on that parameter to a level that is easily met by SiPM technology:

- The counter must be able to determine the mean time of each muon bunch with a time resolution that is much less than the cyclotron period of 150 ns, by at least one order of magnitude.
- The counter must be able to adequately characterize a beam whose intensity ranges from 1% to 200% of the expected 7.3×10^5 muons per fill at the inflector entrance.

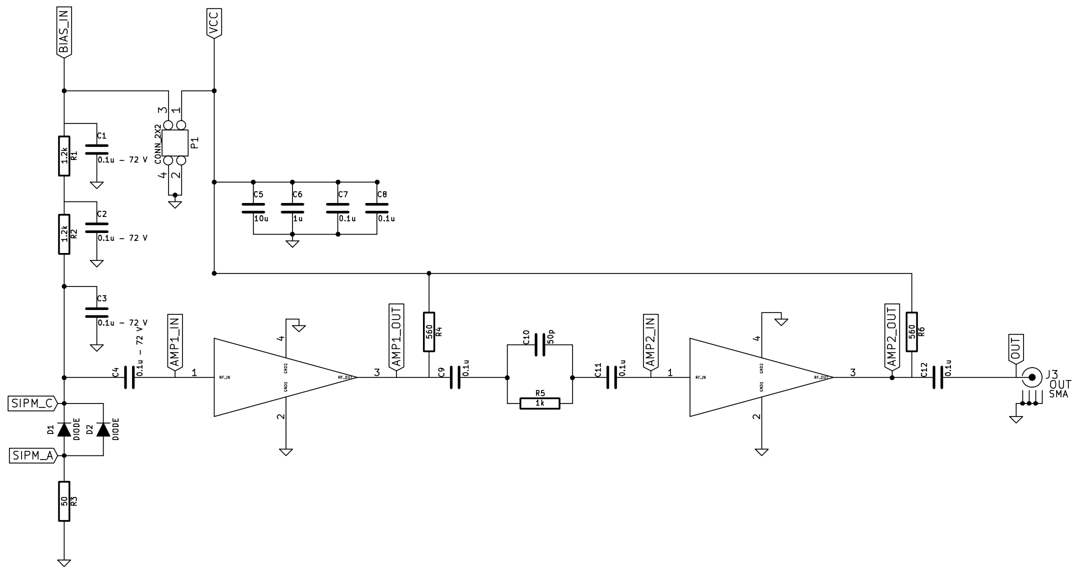
In E821, "flashlets" of beam that leaked from the AGS onto the target during the measuring period led to a potential systematic error. Muons produced by protons from a bunch that had not been cleanly kicked arrived at the experiment at the cyclotron period of the AGS. It is difficult to envision how this phenomenon could arise at Fermilab; any out-of-time muons would somehow need to be stored in the delivery ring without being kicked in. Nevertheless, it is worthwhile to be prepared with an extinction monitor to verify the absence of these out-of-time muons. Such a monitoring detector must satisfy this requirement:

- The counter must be able to detect a single isolated muon following a pulse of up to 200% of the expected 7.3×10^5 muons per fill, after a delay of 10 μs.

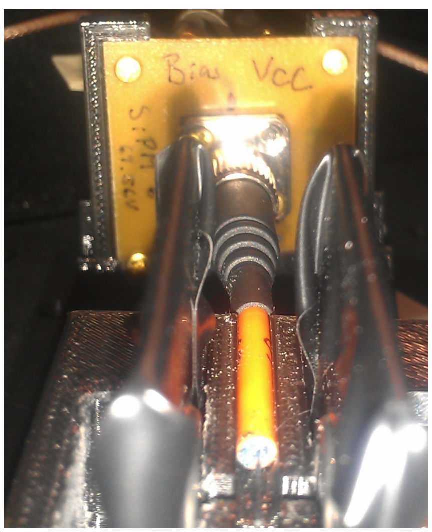
The 10 μs delay is set by the circumference of the recycler ring, which would give any "flashlets" a period of 10.9 μs. It is much longer than the recovery time constant of a SiPM, so it should be easily achievable.

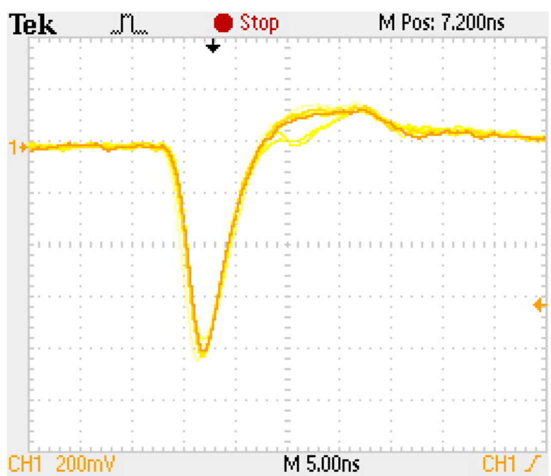
20.2.2 Recommended design

In E821, the primary entrance ("T0") counter consisted of a 1 mm thick, 10 cm diameter volume of Lucite that produced Cerenkov light. It was coupled to a two-inch Hamamatsu



(a)





(b) (c)

Figure 20.5: (a) Schematic of SiPM preamplifier circuit for fiber harps, based on a design from the Paul Scherrer Institute. (b) Photograph of a prototype board with a connectorized scintillating fiber sample attached. (c) Oscilloscope trace of a pulse from it.

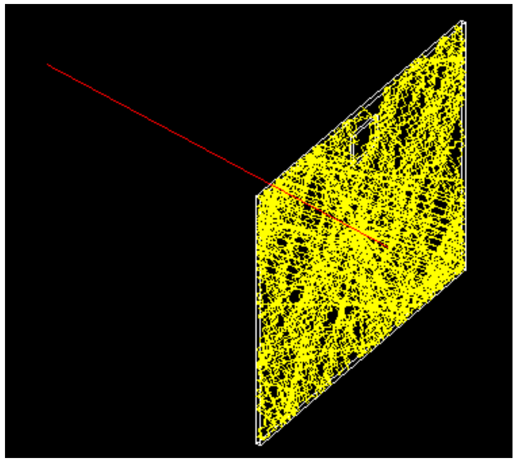


Figure 20.6: Tracking of photons produced by a minimum-ionizing muon in a 1.5 mm thick Lucite Cerenkov counter.

R1828 photomultiplier. It was initially believed that this device could be reused. However, when it was located after transportation to Fermilab, it was found to be damaged beyond convenient repair. Consequently, a new device is needed. The flashlet counter was a plastic scintillation detector that was only used in early runs of E821. The photomultiplier was configured to be gated off at the primary beam injection time by reversing the voltages on two dynodes. Consequently, the gain could be set to observe small amounts of beam entering at later times. Unfortunately, this device was also not found to be in usable condition.

A GEANT4 Monte Carlo simulation of two entrance counter materials was performed. In each case, a beam of 3.1 GeV muons was passed through the center of a 10×10 cm^2 area of a thin sheet of material with a SiPM of 12×12 mm^2 active area glued to the flat side near the edge, as shown in Figure 20.6. Photons from scintillation and Cerenkov processes were tracked, and the result was a Gaussian distribution centered at $N_{Lucite} = 22.4$ photons per muon reaching the SiPM for a 1.5 mm thick Lucite sheet, and $N_{Scint} = 277$ for a 0.5 mm thick Eljen EJ-212 scintillator sheet.

The spectrum of Cerenkov photons in the Lucite extends from 390 to 570 nm; the spectrum of scintillation light from EJ-212 extends from 400 to 520 nm but is peaked near 420 nm. The photon detection efficiency of typical SiPM devices for these wavelengths is approximately 30%. Consequently, approximately 7 detected photoelectrons per muon would be expected for the Lucite, compared to approximately 80 for the scintillator. Realistic indices of refraction were included in the simulation, but the surfaces of the plastic were assumed to be perfectly polished, so this study gives an upper limit on the potential performance of the detector. However, a prototype of this counter has been constructed and is currently being tested with cosmic rays in the laboratory, and the result will be compared to the light yield of a thin scintilator.

Muons deposit an average of 100 keV of ionization energy in a 0.5 mm plastic scintillator. If the full beam intensity of 7.3×10^5 per fill is spread over a 1 cm^2 area, the radiation dose would be about 2×10^{-5} Gy per fill. Significant adverse effects in plastic scintillator are typically seen at the level of 10^4 Gy [9], so the counter would be expected to last for 5×10^8

fills, or approximately 500 days of 12 Hz operation. This is well-matched to the expected duration of the experiment, although it may require replacement at some point.

We will therefore adopt as a baseline plan to build the entrance counter from a 0.5 mm thick EJ-212 plastic scintillator. It will have two positions to attach light detection devices, either photomultipliers or SiPMs. One of these devices will be used as on the calorimeter, coupled to the scintillator without attenuation; this will play the role of the flashlet counter. The other position will have a slot in front where a neutral density filter can be placed to attenuate the light to produce a linear response to the primary beam pulse; his will be the T0 counter. As the beam is tuned and the intensity increases, it will be possible to change the neutral density filter to match. The signals from each of these detectors will be routed to spare channels of the new calorimeter waveform digitizers.

20.3 Performance

The existing fiber beam monitors were used in E821. They fulfilled the requirements of that experiment, which were very similar to those proposed here.

The SiPM upgrade to the fiber beam monitors will further increase the number of detected photons and therefore improve the signal-to-noise ratio. However, the performance was already sufficient to directly observe and characterize the coherent betatron motion, which was published as Figure 21 in [5].

In E821, the fiber beam monitors were not prepared for the first day of the run. We will ensure that all of these detectors are ready for the first day of muon beam operation so that they can fulfill their requirements as beam commissioning devices. They can be used in this role to monitor the amplitude of the coherent betatron motion as a function of the injection and kick parameters.

20.4 Alternatives

Initially, we evaluated reusing the conventional photomultipliers that were used with the fiber beam monitors in E821. In that experiment, a $\sim$3 m long fiber connected each of the fibers from the feedthrough to an Amperex XP2202/B photomultiplier tube that was located in a cable tray above the storage ring in a location where the magnetic fringe field could be shielded with mu-metal. The signals were small enough that various models of LeCroy linear amplifiers in an adjacent NIM crate were needed to drive the long cables to the counting room. The photomultipliers and voltage divider bases that were used in E821 had already been reused from a previous project, and they are clearly aging devices that are in need of replacement. An initial inspection showed that they are in poor condition and unsuitable for future use. It would have been necessary to develop a new light conversion system, whether or not we moved to SiPM technology. Given the collaboration's familiarity with SiPMs from their extensive use in the calorimeter development (discussed in Section 17.4), their compactness, and their comparatively low cost, there was a clear choice.

The fiber beam monitor is not suited for a determination of the equilibrium radius of the stored beam. A GEANT4 simulation showed that energy loss in the fibers moves the

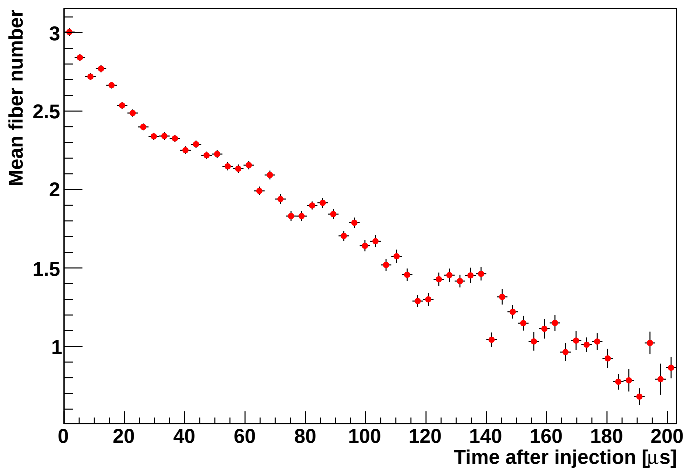


Figure 20.7: Simulated radial beam centroid position, in units of fiber number (7 mm), when the fiber harps are inserted. Energy loss in the fibers causes the beam to shift radially inward.

average radius inward by $\sim$0.1 mm/μs, so the radius will be altered before equilibrium can be established. Even an order of magnitude less energy loss would still be unacceptable for this measurement, so it is not plausible that any system that intercepts the beam would be useful for it. We briefly considered diagnostic devices that would remain continuously deployed in the storage ring. However, any detector that intercepts the muons, even a low-mass wire chamber, would degrade the beam lifetime unacceptably, as shown in Figure 20.7. The E821 experience with a completely parasitic detector, the pickup electrodes, was also unsatisfactory; they were paralyzed by the pulsed high voltage devices.

We had previously proposed to use waveform digitizers from the MuLan experiment [8] to read out the auxiliary detectors. They were existing devices that could have been obtained at no cost. However, we recognized that there would be significant value in simplifying the data acquisition system and the clock and control system distribution by using only one model of waveform digitizer. In the end, we determined that the time and effort that would have been required to install and support the MuLan system was not justified by the initial savings on the hardware.

Similarly, although we have acquired a set of SiPMs that could be used for the fiber readout, a new technological generation with significantly less dark current and greater photon detection efficiency is now available. This would also allow us to reconsider the most appropriate number of pixels in the device; as shown above, saturation of a 400 pixel SiPM may become a concern. We have recently obtained samples of Hamamatsu S12571-025C devices to test, which have 1600 pixels, and we are continuing to evaluate the value of purchasing this new model.

In E821, the primary method of monitoring the rate of flashlets was to suppress the firing of the electrostatic quadrupoles periodically, preventing the injected muon bunch from being stored. The number of suppressed fills could be varied, but it was typically one out of 25. Any signals that appeared in the calorimeters during these fills were presumed to be from flashlets, which was verified by observing the cyclotron period of the AGS in the time structure of the signals. While this method is effective, it unnecessarily discards a few percent of the data.

20.5 ES&H

The most significant hazards associated with the auxiliary detectors are electrical. The bias voltages needed for the SiPM readout of the fiber beam monitors will be approximately 70 V. To mitigate this hazard, a current-limited power supply will be used, with the current limit set to the lowest value that allows the devices to operate. All electrical devices will be subject to Fermilab's standard design review and operational readiness clearance processes.

The fiber beam monitors will be powered by compressed air at less than 150 psi. Requirements for appropriate personal protective equipment, such as eye protection, when working around compressed air lines will be determined in consultation with Fermilab ES&H experts. Similarly, the fiber beam monitors interface with the ultra high vacuum system, and they are within the large fringe field of the storage ring magnet. We will work with Fermilab ES&H to establish appropriate procedures to mitigate these hazards. The vacuum test stand to be used in laboratory tests before installation is small enough (less than 12 inch inner diameter and 35 cubic foot volume) to fall outside the scope of Fermilab's vessel certification requirements.

During the laboratory design and construction phase, other hazards will be relevant. Tools, including some with sharp blades as well as soldering irons and hot air stations, will be needed and will be treated with due caution. Two-part optical cement will be used to bond the fibers; it, and any other chemicals that are needed, will be handled in accordance with the requirements in the MSDS. Low-activity radiation sources will be used to test the light output of scintillating fibers, following the usual radiation safety precautions.

20.6 Risks

There is a risk of hidden damage, or degradation over time, to the fiber beam monitors that might require more repair work than anticipated. This damage may not be discovered until mechanical, vacuum, and light output tests are completed. There is also a risk that, after testing, we may find that the SiPMs that we were able to acquire at no cost are not suitable for the application and that we need to procure another model.

However, the only risk that would be expected to have a noticeable impact on the total project cost would be the destruction or damage beyond repair of one or more of the existing fiber harp devices by an accident in shipping, storage, or testing. Because much of the original knowledge of the system has been lost, to re-create a fiber beam monitor from scratch would require a significant level of unplanned engineering cost in addition to the precision machining work.

Because the fiber beam monitors interface with the beam vacuum system, any leak could cause downtime for the experiment. The motion control system could potentially fail in a way that would not allow them to be retracted, which would also cause downtime, requiring the entire storage ring to be brought up to atmospheric pressure to remove them. We intend to minimize these risks by careful testing before installation.

20.7 Quality Assurance

We will test the motion and vacuum integrity of the fiber beam monitors with extensive exercises in a test chamber in the laboratory before they are installed in the storage ring. We will also check the output of each fiber, and therefore the functionality of each SiPM channel, with a set of light pulsers and radiation sources.

20.8 Value Management

The auxiliary detectors represent a successful application of value management principles. All components that are suitable for reuse from Brookhaven E821 will be reused. The primary upgrade to the fiber beam monitor devices will be a SiPM readout system. For that installation, suitable unused SiPM devices (spares from a previous project) were identified and made available by Argonne National Laboratory.

20.9 R&D

The following studies are in progress or will begin very soon, in summer 2015:

- We are continuing to characterize techniques for bonding scintillating fibers to clear fibers and to check the transmission of light through the clear fibers and the vacuum feedthroughs.
- We will vacuum leak-test each of the fiber harp stations.
- We will repair the known mechanical damage to one fiber harp and proceed to verify that it moves correctly.
- We will build and test the final SiPM preamplifier design, along with a final version of the part that will hold it onto the fiber outside the vacuum feedthrough.
- We will develop a final version of the motion control system for the plunging of the fiber harps that interfaces with the experiment's MIDAS Slow Control Bus network.
- We will build prototypes of the new entrance counters with both 1.5 mm Lucite and 0.5 mm EJ-212 scintillator, and we will test them with cosmic rays to determine the light yield. This will allow the simulation to be validated. In the event that the performance of the prototype is sufficient to meet the requirements of the experiment, it will become the final entrance counter.

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